

# *Neutrino Telescopes: Physics and Astrophysics*

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# Neutrino Telescopes

- Present: IceCube(+DeepCore), SuperKamiokande  
Future: extensions (PINGU, HyperKamiokande)  
+ new experiments/techniques
- High energy neutrinos from astrophysical sources detected!
  - Want to understand:
    - astrophysics:
      - origin, source characteristics, relation to cosmic rays, gamma rays, etc.
    - physics:
      - sensitivity to new interactions
      - tests of fundamental symmetries (Lorentz, etc.)
  - Dark matter annihilation

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  - lots of them; “background”, but useful!
  - physics:
    - “short term”: could get to mass ordering first
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      - crucial consistency check in
        - testing framework
        - search for new physics
  - astrophysics:
    - atmospheric neutrino production in cosmic ray interaction
    - better understanding of background for astrophysical searches

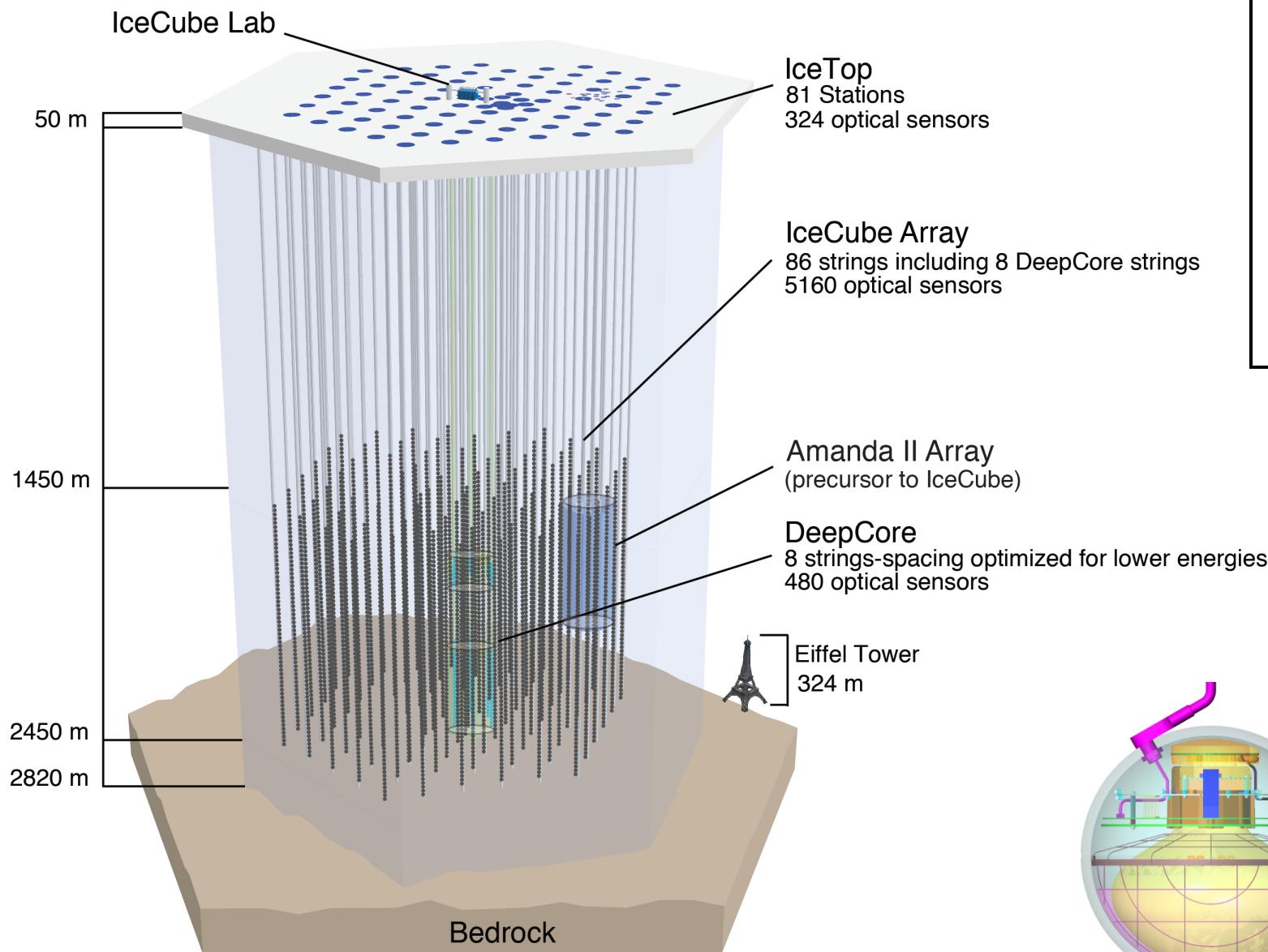
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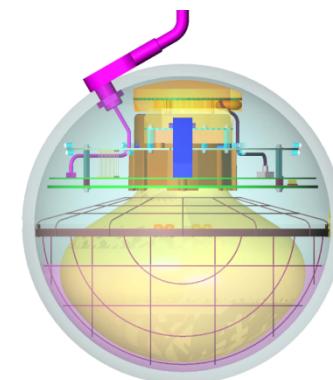
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# The IceCube Neutrino Observatory



Configuration chronology

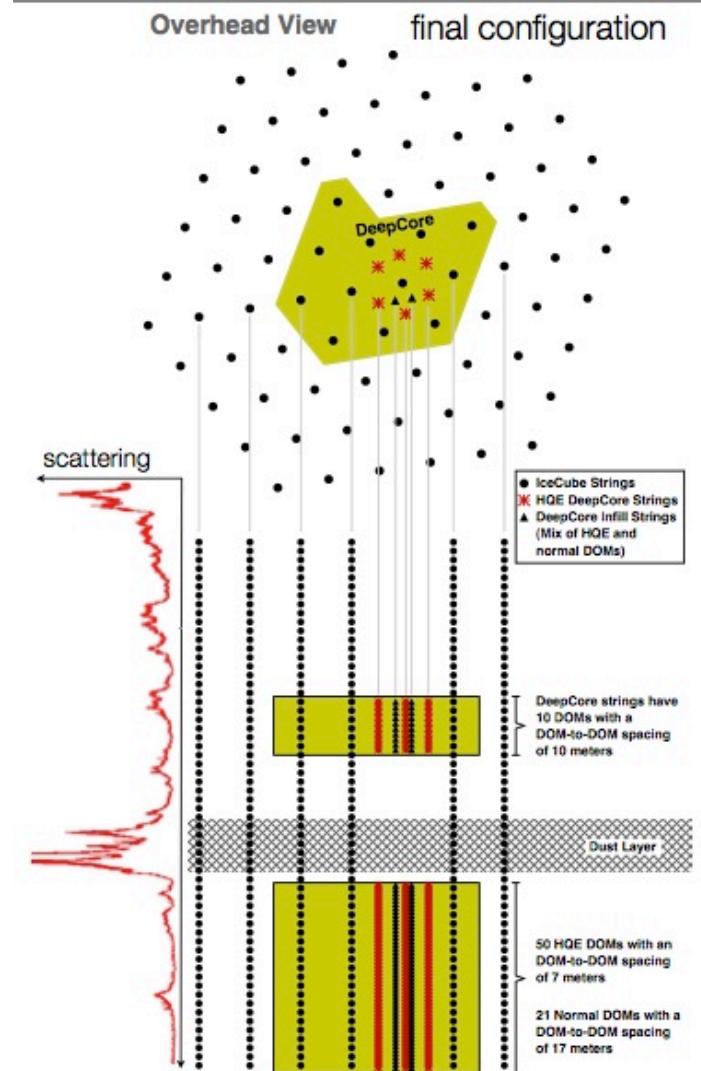
2006:	IC9
2007:	IC22
2008:	IC40
2009:	IC59
2010:	IC79
2011:	IC86



Digital Optical Module (DOM)

# IceCube Deep Core

- motivation: look for neutrinos from galactic sources, dark matter annihilation
  - galactic center is above horizon at South Pole
  - need to reduce large cosmic muon background
- $4\pi$  coverage  
look at down-going events,  
study galactic sources, galactic center
- 8 special strings, 72m IS, 7m DOM spacing
- ~ 5x higher effective photocathode density
- ~ 20Mton
- IceCube's top and outer layers: active veto



- Up to 100,000 events/year! Use them!
- Energy range 10-40 GeV great for oscillation physics
- Statistics compensate for systematics for many issues
  - Use energy and angular distributions sensitive to physics
  - Normalizations can be determined from data

PHYSICAL REVIEW D **78**, 093003 (2008)

## **Neutrino mass hierarchy extraction using atmospheric neutrinos in ice**

Olga Mena,<sup>1,2</sup> Irina Mocioiu,<sup>3</sup> and Soebur Razzaque<sup>4</sup>

<sup>1</sup>*INFN Sez. di Roma, Dipartimento di Fisica, Università di Roma “La Sapienza”, P.le A. Moro, 5, I-00185 Roma, Italy*

<sup>2</sup>*Institute of Space Sciences (IEEC-CSIC), Fac. Ciencies, Campus UAB, Bellaterra, Spain*

<sup>3</sup>*Department of Physics, Pennsylvania State University, University Park, Pennsylvania 16802, USA*

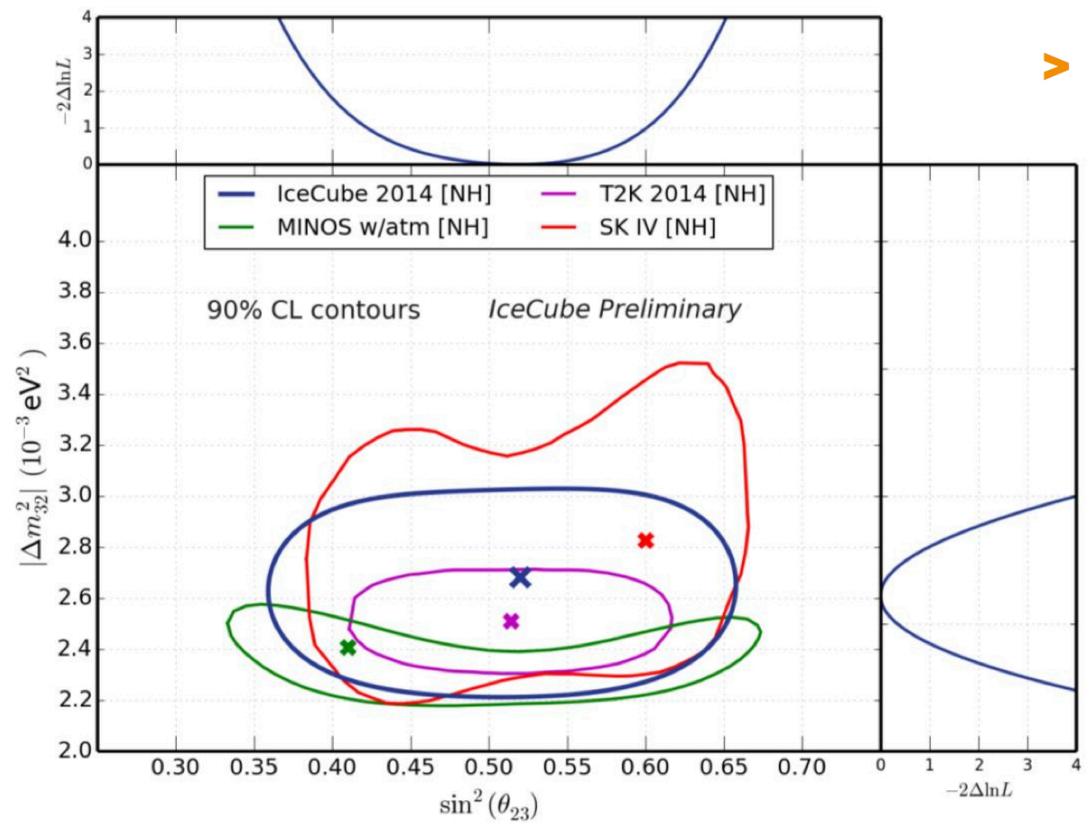
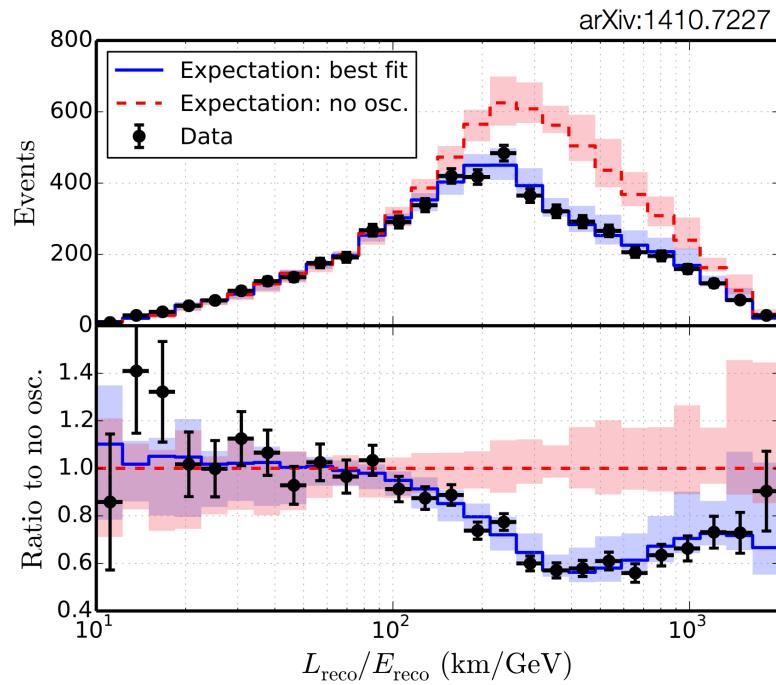
<sup>4</sup>*Space Science Division, Code 7653, U.S. Naval Research Laboratory, Washington D.C. 20375, USA*

(Received 27 March 2008; published 6 November 2008)

We show that the measurements of 10 GeV atmospheric neutrinos by an upcoming array of densely-packed phototubes buried deep inside the IceCube detector at the South Pole can be used to determine the neutrino mass hierarchy for values of  $\sin^2 2\theta_{13}$  close to the present bound, if the hierarchy is normal. These results are obtained for an exposure of 100 Mton years and systematic uncertainties up to 10%.

- Data already there: need the right tools to analyze it

# IceCube Deep Core Neutrino Oscillation Results

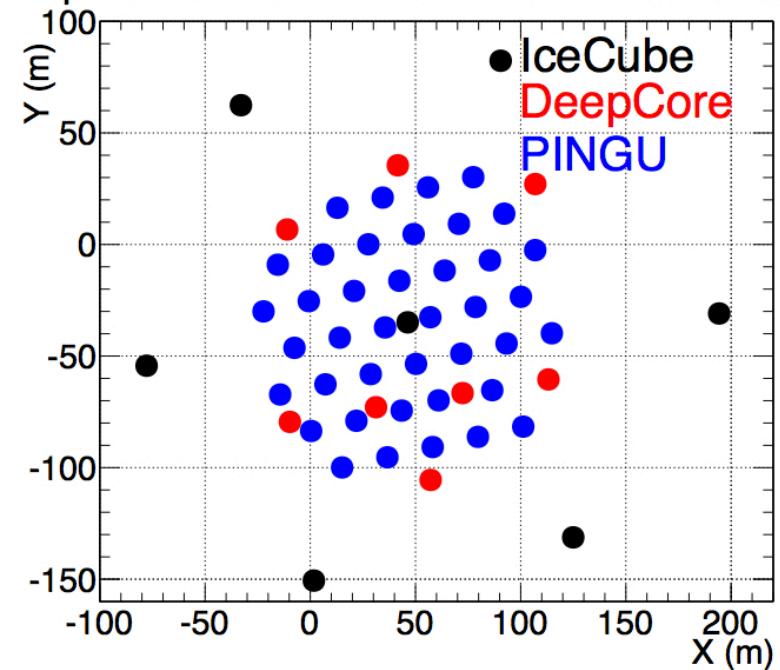


# PINGU



- Baseline detector consists of 40 additional strings of 60 Digital Optical Modules each, deployed inside the DeepCore volume
  - Geometry optimization underway – additional DOMs have relatively low incremental cost – final proposal likely 80-96 DOMs/string
  - 20-22 m string spacing (cf. 125 m for IceCube, 72 m for DeepCore)
  - ~25x higher photocathode density
  - Additional in situ calibration devices will better control detector systematics (not included in projected performance)
- Engineering issues and cost of deploying instrumentation are well understood from IceCube experience
  - Can install  $\geq 20$  strings per season once underway

Top view of the PINGU new candidate detector



Ty DeYoung

# ICDC/PINGU

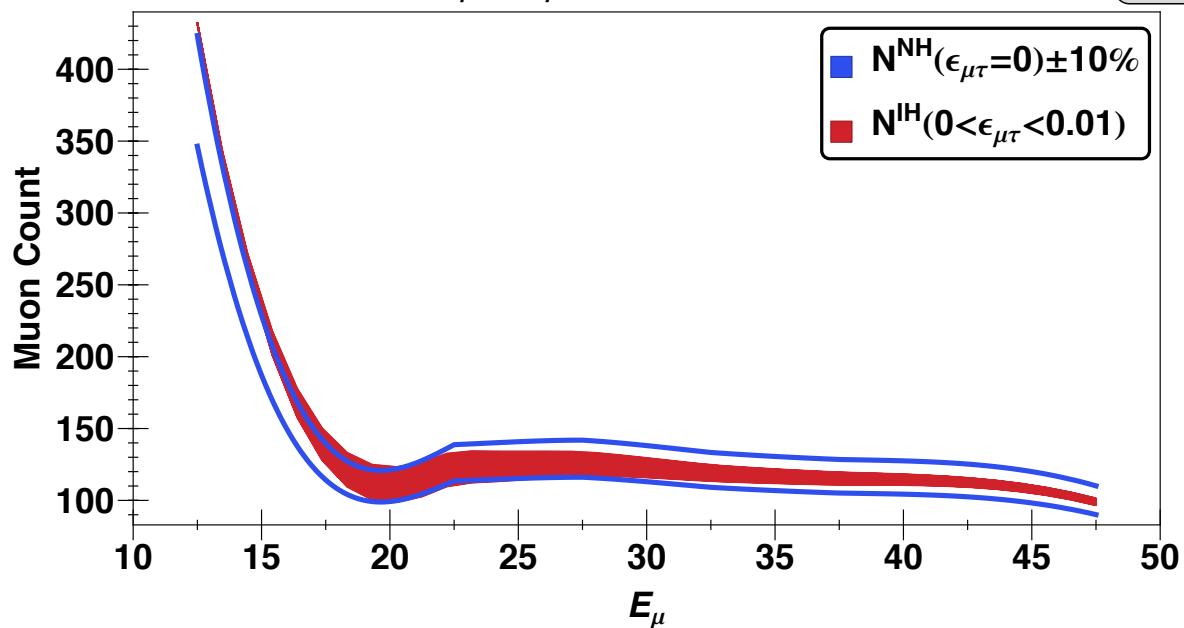
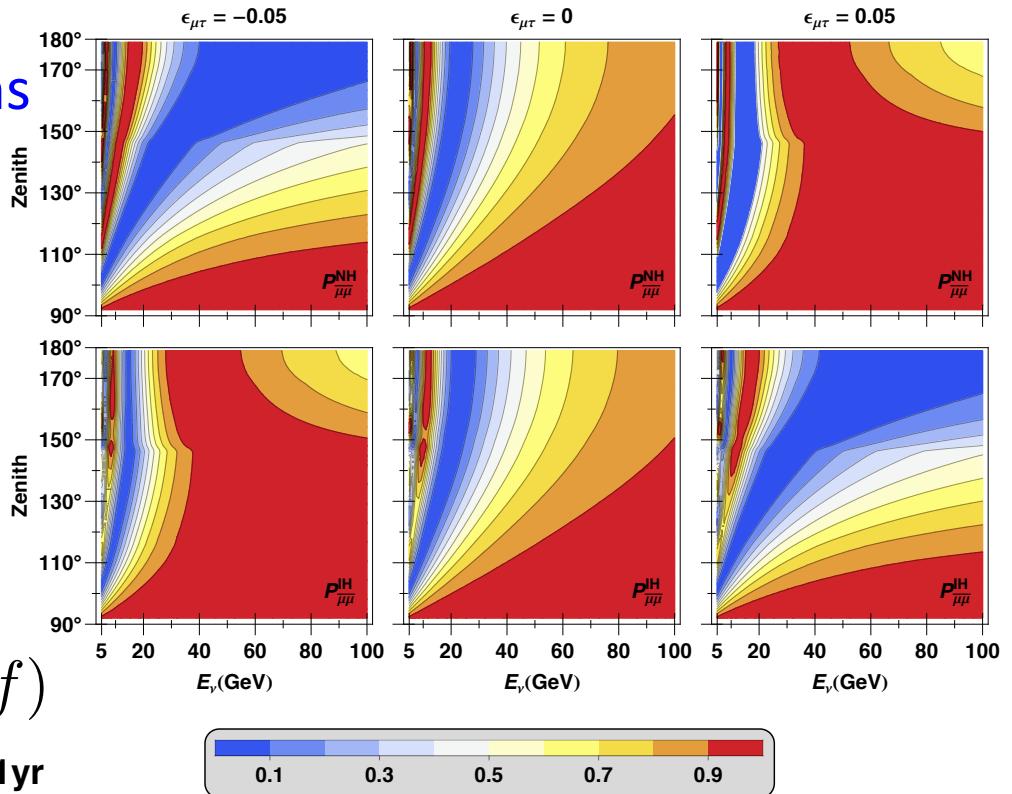
- mass hierarchy (O.Mena, I.Mocioiu, S.Razzaque, Phys. Rev. D78(2008) 093003)
- precision on all parameters  
(G. Giordano, O.Mena, I.Mocioiu, Phys. Rev. D82 (2010) 093001)
- tau neutrino appearance  
(G. Giordano, O.Mena, I.Mocioiu, Phys. Rev. D81 (2010) 113008)
- new physics in neutrino sector
  - large range of energies
  - large range of distances
  - high densities: matter effects

# Non-standard neutrino interactions

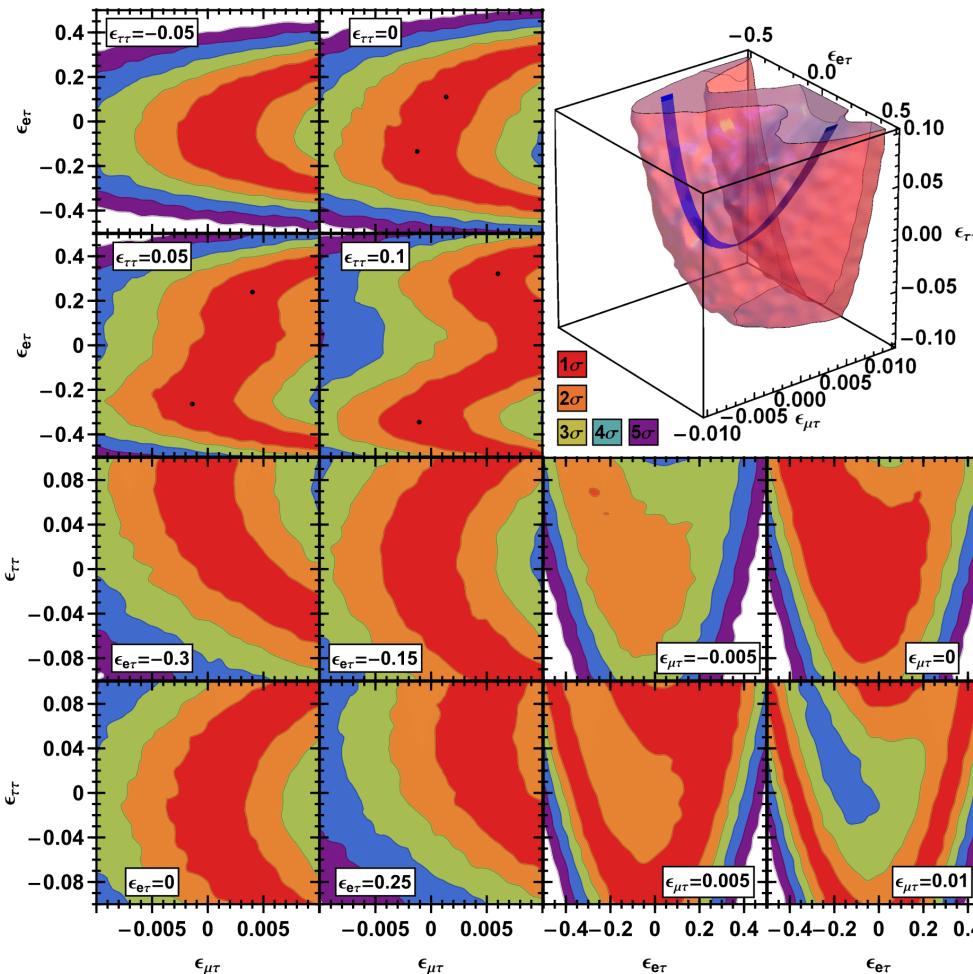
I.Mocioiu, W.Wright, arXiv:1410.6193

understand degeneracies  
and  
how to break them

$$\mathcal{L} = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma^\rho \nu_\beta) (\bar{f} \gamma_\rho f)$$

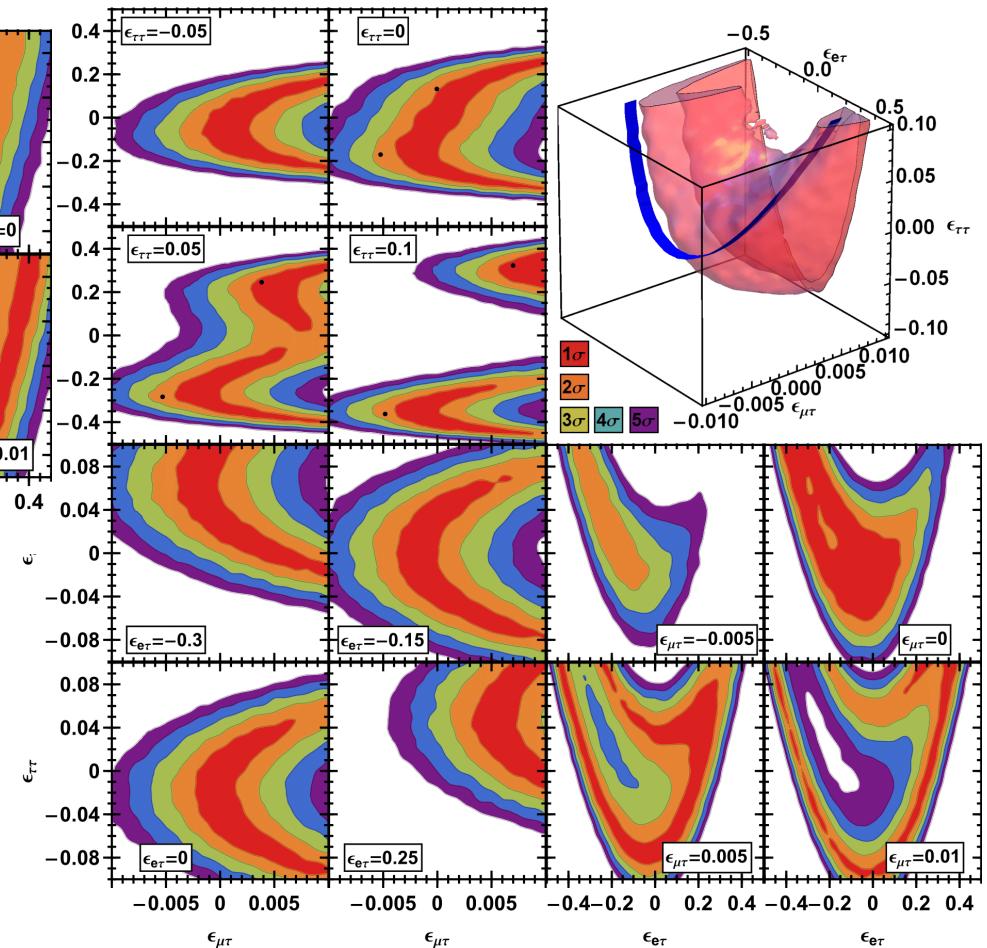


$\chi^2$  from ICDC  $N_\mu^{\text{NH}, \text{null}}$  vs.  $N_\mu^{\text{NH}}$  for High energy  $\nu_\mu$  through Core. Source:  $P_{\mu\mu}$  only.



NSI  
e-tau  
mu-tau  
tau-tau

$\chi^2$  from ICDC  $N_\mu^{\text{NH}, \text{null}}$  vs.  $N_\mu^{\text{NH}}$  for low energy  $\nu_\mu$  through Core. Source:  $P_{\mu\mu}$  only.



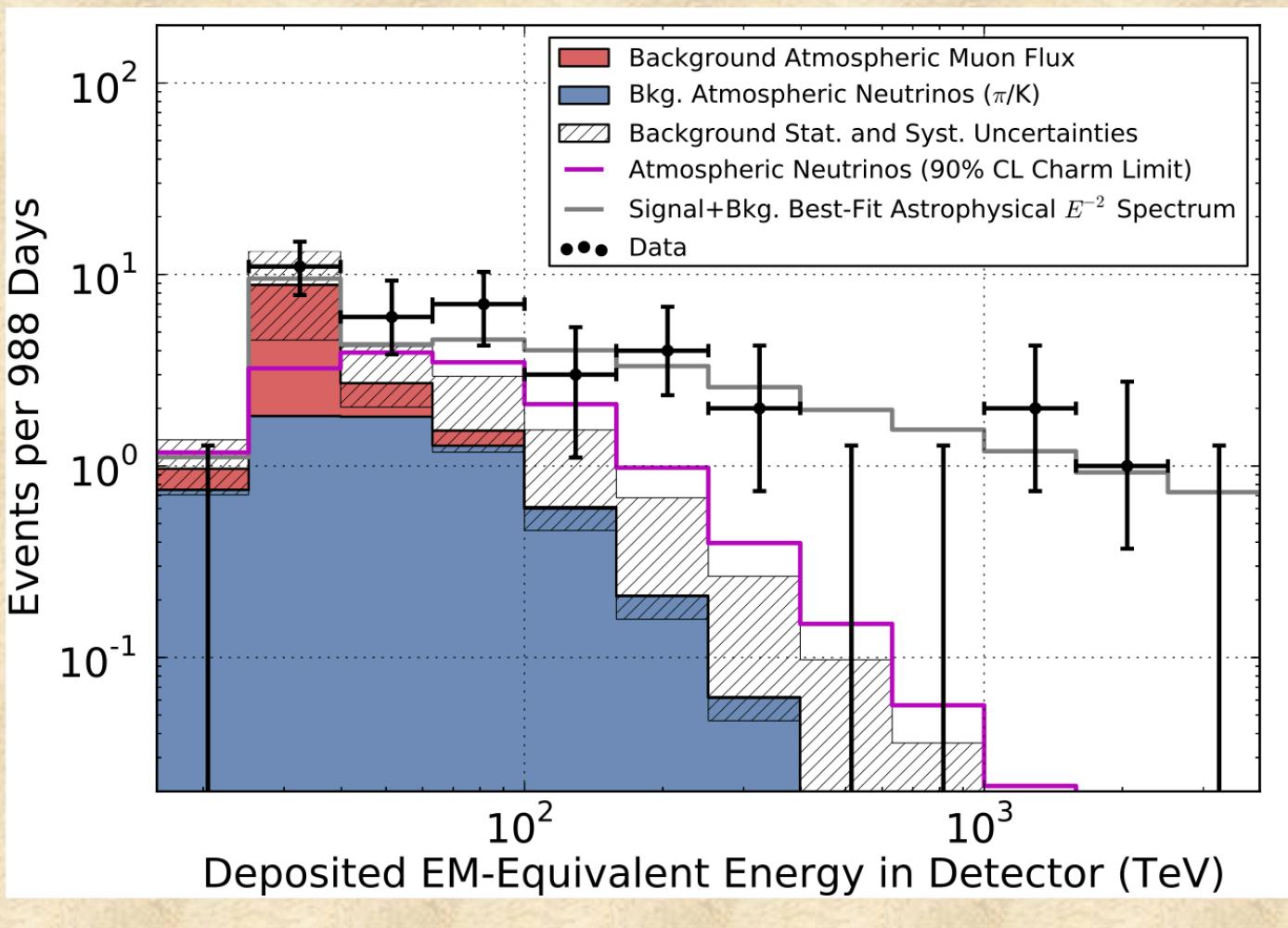
# Neutrino Telescopes

- Atmospheric neutrinos
  - High statistics
  - physics:
    - “short term”: could get to mass ordering first
    - “long term”: can measure mass ordering
      - could measure octant
      - could get tau neutrino appearance
      - crucial consistency check in
        - testing framework
        - search for new physics
- To get physics optimize (PINGU):
  - energy resolution
  - some directional reconstruction
  - energy threshold: more physics vs systematics at low energy

Neutrino astronomy is becoming reality!

# HESE 3 Year Results

best-fit per-flavor astrophysical( $E^{-2}$ ) flux  
in the energy range of 60 TeV – 3 PeV  
 $E^2\phi(E) = 0.95 \pm 0.3 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$

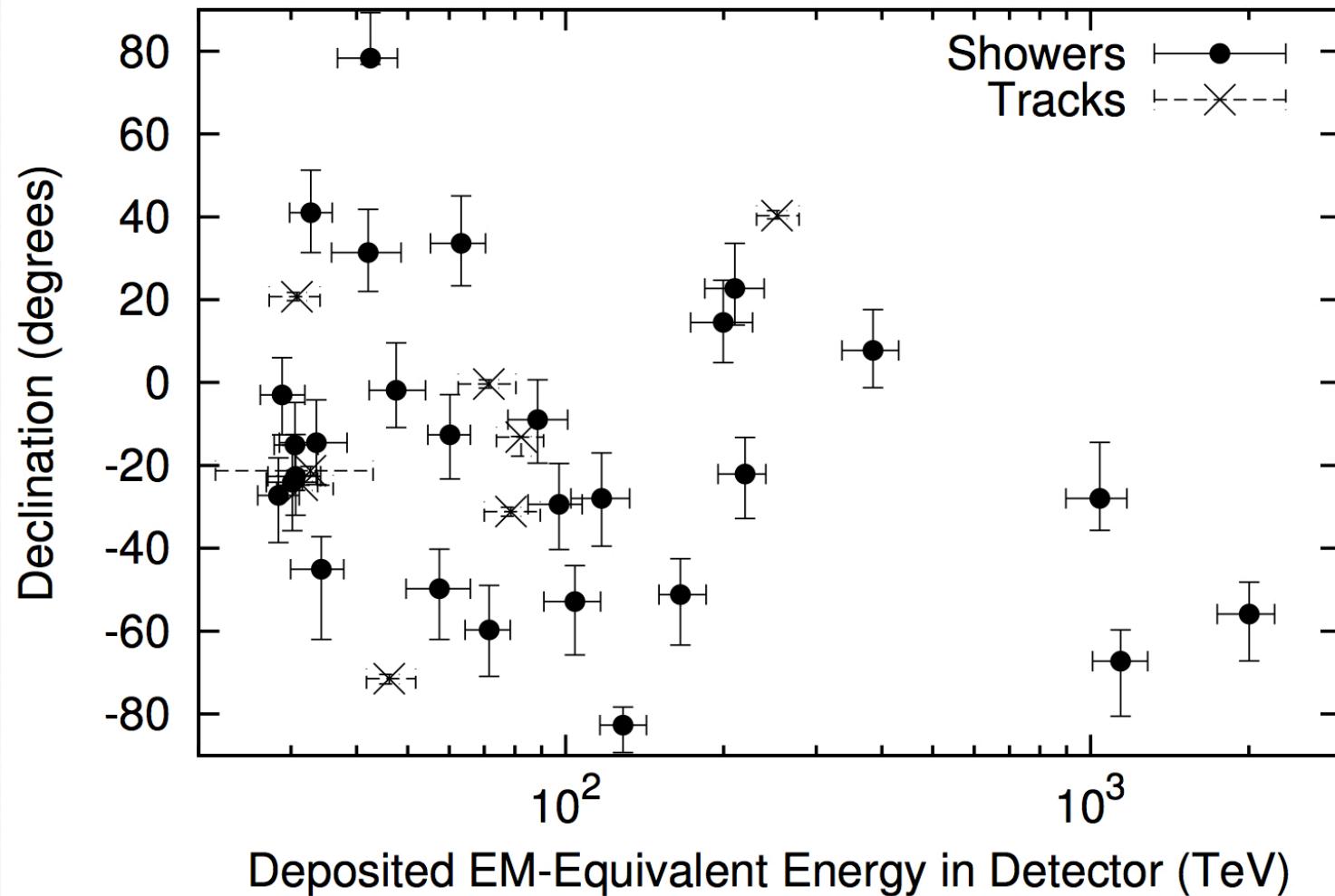


- consistent with  $E^{-2}$
- indication of a cutoff around 2 PeV above which 4.1 events would be expected from a flux at our best-fit level
- The range of best fit slopes of -2.0 to -2.3.

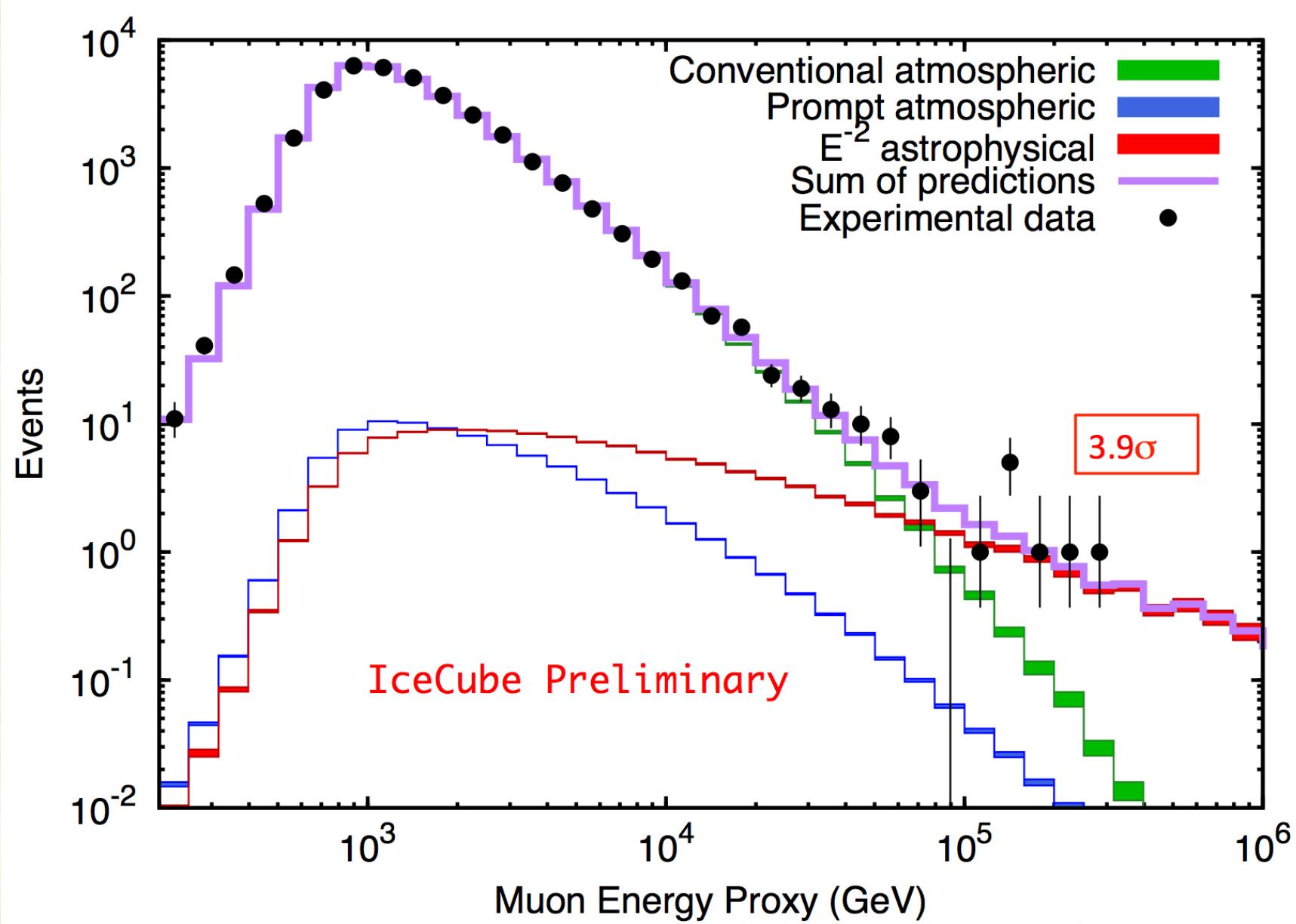
# Updated HESE Results (3 Year)

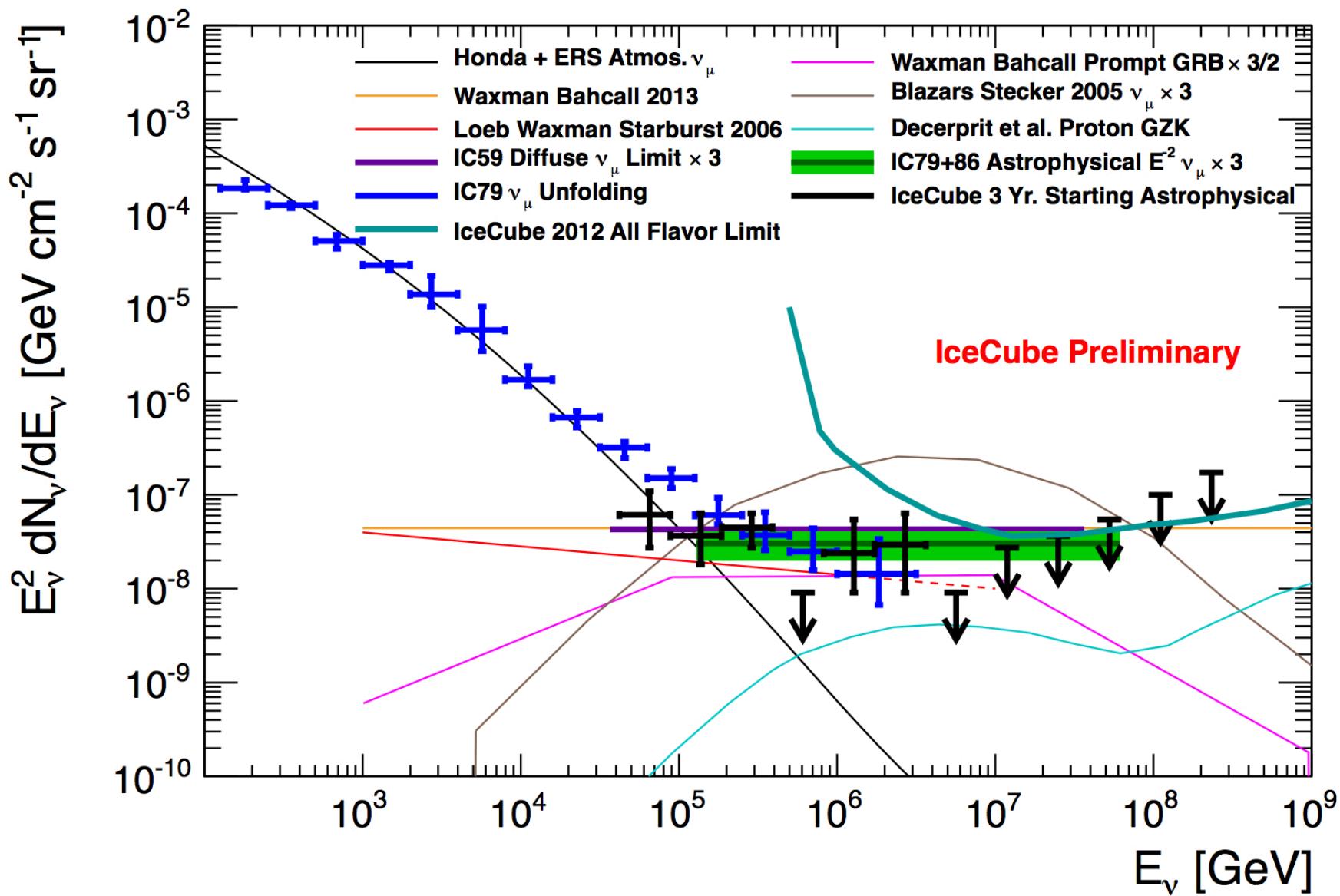
- 988 day sample
- detected 37 events
- expected background of  $8.4 \pm 4.2$  cosmic ray muon events and  $6.6+5.9$  atmospheric neutrinos.

5.7 $\sigma$

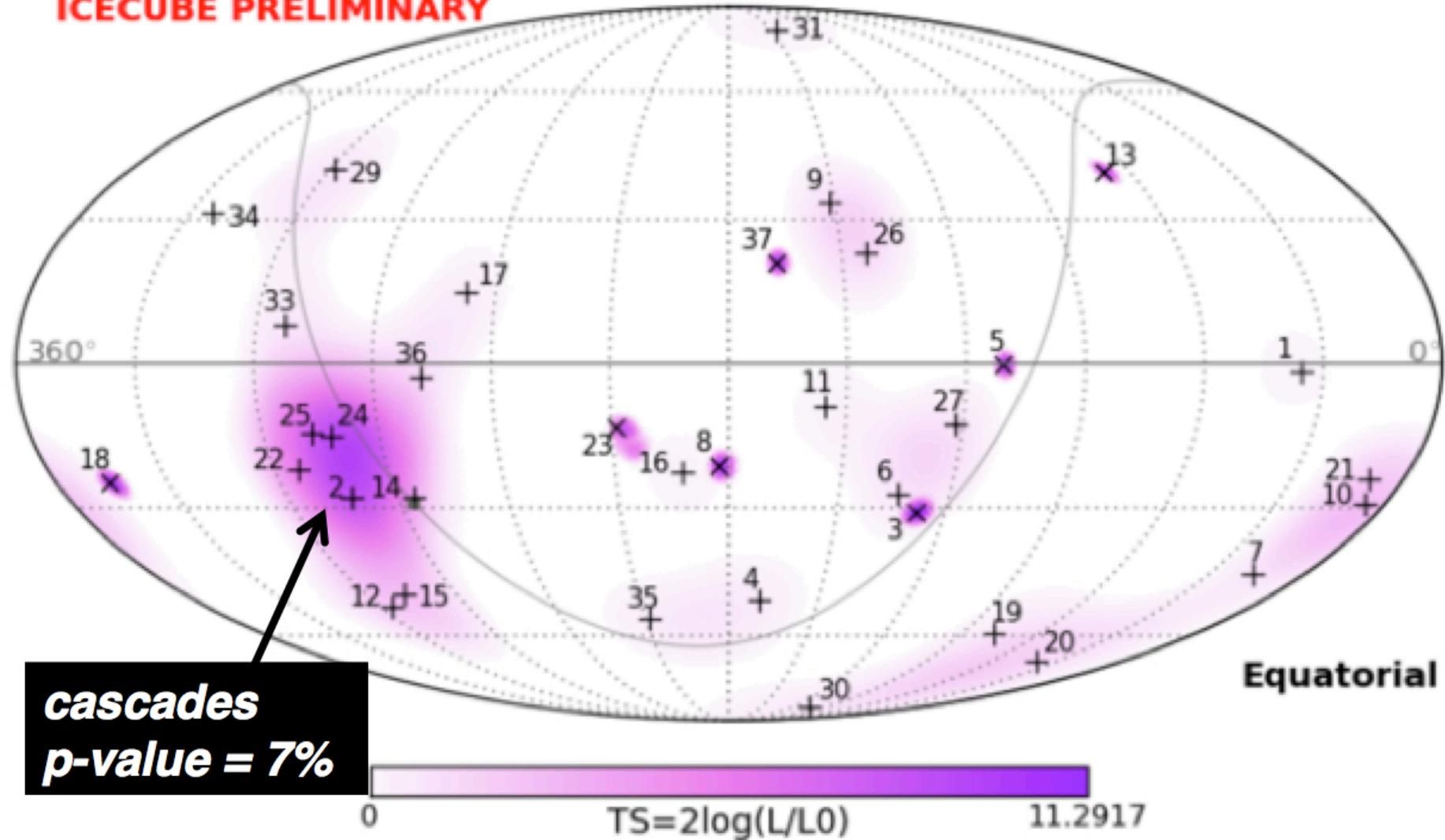


# IC79,86-1 $\nu_\mu$ diffuse neutrinos





ICECUBE PRELIMINARY



**cascades**

**p-value = 7%**

0                             $TS = 2\log(L/L_0)$                             11.2917

## Neutrino astronomy

- Becoming real!
- Flux close to expected level from PeV-level cosmic accelerator  
Which ones? Many models, none conclusive yet
- Valuable information (not yet sufficient):
  - energy spectrum not  $1/E^2$   
cannot yet differentiate between steeper/broken power law
  - flavor composition not yet conclusive
  - arrival direction
- Need detailed studies of many possibilities
- Need more data/better veto/better event characterization
- Neutrino astronomy is now becoming reality!

# Neutrino Telescopes

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  - Want to understand:
    - astrophysics:
      - origin, source characteristics, relation to cosmic rays, gamma rays, etc.
    - physics:
      - sensitivity to new interactions
      - tests of fundamental symmetries (Lorentz, etc.)
- Need:
  - pointing: astronomy – identify sources
  - energy spectrum: could differentiate astrophysics/physics effects
  - flavor composition: information about physics/astrophysics